Report 2175

SHOCK EFFECTS ON INTERFACES

April 1976

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Over 100 successful hypervelocity impacts (at 2 to 10 km/s) have been made on steel armor in the NRL light gas-gun facility. The projectiles were approximately 0.5- to 1.0-gram spheres and other shapes of nylon, water, steel, ceramics, and other materials. The objective was to develop a better understanding of the physics of spallation. Numerous phenomena were delineated, such as the $\alpha \rightleftarrows \epsilon$ phase change, crater floor serrations and macrocracks, adiabatic shear, voids, and backface spallation. Predictive heuristic theory was developed. It is concluded that it is feasible to design a hypervelocity projectile that optimizes backface spall and fragmentation.

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CONTENTS

SHOCK EFFECTS ON INTERFACES

I. INTRODUCTION

1. **General.** From February 1972 through April 1974, the U.S. Army Mobility Equipment Research and Development Command (MERADCOM) had subjected over 100 specimens of armor steel to successful impacts at hypersonic velocities[1] in the Naval Research Laboratory light gas-gun facility. The immediate purpose of these experiments was to develop heuristic theory capable of predicting backface spall and associated phenomena resulting from impacts of small projectiles. The long-range objective was to obtain sufficient understanding of the impact phenomena to enable the design of projectiles (or spallators) capable of optimizing the backface spall for the purpose of producing damage to components inside of military vehicles.

Results and analyses of most of the experiments performed prior to December 1973 have been reported previously.[2-6] In this report, phenomena peculiar to interfaces and results obtained between December 1973 and April 1974 are reported.

II. BACKGROUND

2. **Summary of Hypervelocity Impact Experiments.** Projectile material, shape, size, configuration, velocity, and impact angle were variable. In all, 36 experiments were performed using nylon spheres as projectiles, 14 using steel spheres, 14 using liquid-filled polymer shells, and the remainder using special projectiles of various shapes, sizes, materials, and configurations. These special projectiles included spheres of titanium, glass, Al_2O_3, tungsten carbide (WC), magnesium-lithium (MgLi), hollow Lexan and steel spheres, hollow and solid Lexan cylinders, and Lexan cylinders with steel tips.

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1 Hypersonic velocities or hypervelocities imply velocities of about 2 to 10 km/s. The terms are misnomers but are used widely.

2 J. W. Bond, Jr., "Shock Damage and Back Face Spall in Materials," *Proceedings of the Army Symposium on Solid Mechanics*, 1972, Army Materials and Mechanics Research Center Report, AMMRC MS 73-2, September 1972.

3 J. W. Bond, Jr., and G. W. Ullrich, *Two-Dimensional Spallation Induced by Hypervelocity Impact in Wrought Steel Plate*, U.S. Army Mobility Equipment Research and Development Center Report 2067, July 1973.

4 J. W. Bond, Jr., "Hypervelocity Impact Shock-Induced Damage to Steel Armor," Army Science Conference, West Point, N.Y., June 1974.

5 J. W. Bond, Jr., *High Pressures Induced by Short-Pulse Lasers*, U.S. Army Mobility Equipment Research and Development Center Report 2080, November 1973.

6 D. A. Shockey, *et al.*, *Physical Changes Occurring in Armor Steel Under Hypervelocity Impact*, Stanford Research Institute Final Report on USAMERDC Contract DAA D05-73-C-0025, March 1974.

The diameter D of the nylon spheres varied from 0.795 to 1.91 centimeters, but most of the experiments used spheres with diameters of 0.953 and 1.19 centimeters. The steel spheres had diameters ranging from 0.554 to 1.153 centimeters, and liquid-filled Lexan spheres had diameters between 0.86 and 1.0 centimeter.

Target materials included 1.27-, 2.54-, and 3.81-centimeter-thick rolled homogeneous armor corresponding to MIL-S-12560B steel, 3-centimeter-thick cast armor corresponding to MIL-S-11356D, 3.81-centimeter-thick Soviet rolled homogeneous steel armor, 1.25-centimeter-thick Electro Slag Remelt (ESR) steel, and 1.27-centimeter-thick MS-12560 steel backed by 1.27-centimeter-thick Plexiglas (used in two separate experiments).

3. **Summary of Previous Results.** As indicated earlier, the prime objective of these experiments was to learn more about the physics and metallurgy of backface spall. However, these were numerous "surprises," most of which have not been explained satisfactorily. These various findings will be summarized briefly in this section.

A schematic diagram of the impact damage geometries is shown in Figure 1. Most of the experiments resulted in craters and spall layers as depicted in Figure 1, part (a), which is representative of a 0.95-centimeter nylon sphere impacting MS-12560 steel at 4 to 5 km/s. The serrations noted on the crater floor are quite regular for nylon-on-steel impacts. These serrations have not been explained, but it is suggested that they might be due to dynamic instabilities. They do not exist for steel-on-steel impacts. This difference also has not been explained. The large macrocracks shown extending below the crater floor start at the serration valleys and always go in the direction indicated, i.e., toward the rear surface of the target and toward the crater center line. Similar macrocracks exist for steel-on-steel impacts, but they go upward toward the front surface of the target and away from the crater centerline. In either case, the macrocracks have not been explained; in particular, the reason for the marked difference between the nylon-on-steel and the steel-on-steel macrocracks is unknown. There is a dark, spherically symmetric region below the crater floor that approximately covers the region penetrated by the macrocracks. In this region, the hardness is about twice that of the unshocked steel, and the grain structure is much finer. Although there is no direct experimental proof, it is generally agreed that this is the 130-kilobar $\alpha \rightleftarrows \epsilon$ phase change observed in iron and in martensitic steels. This is also in agreement with detailed 2-d computations made by Sandia Laboratories.[7]

[7] D. A. Shockey, *et al.*, *Physical Changes Occurring in Armor Steel Under Hypervelocity Impact*, Stanford Research Institute Final Report on USAMERDC Contract DAA D05-73-C-0025, March 1974.

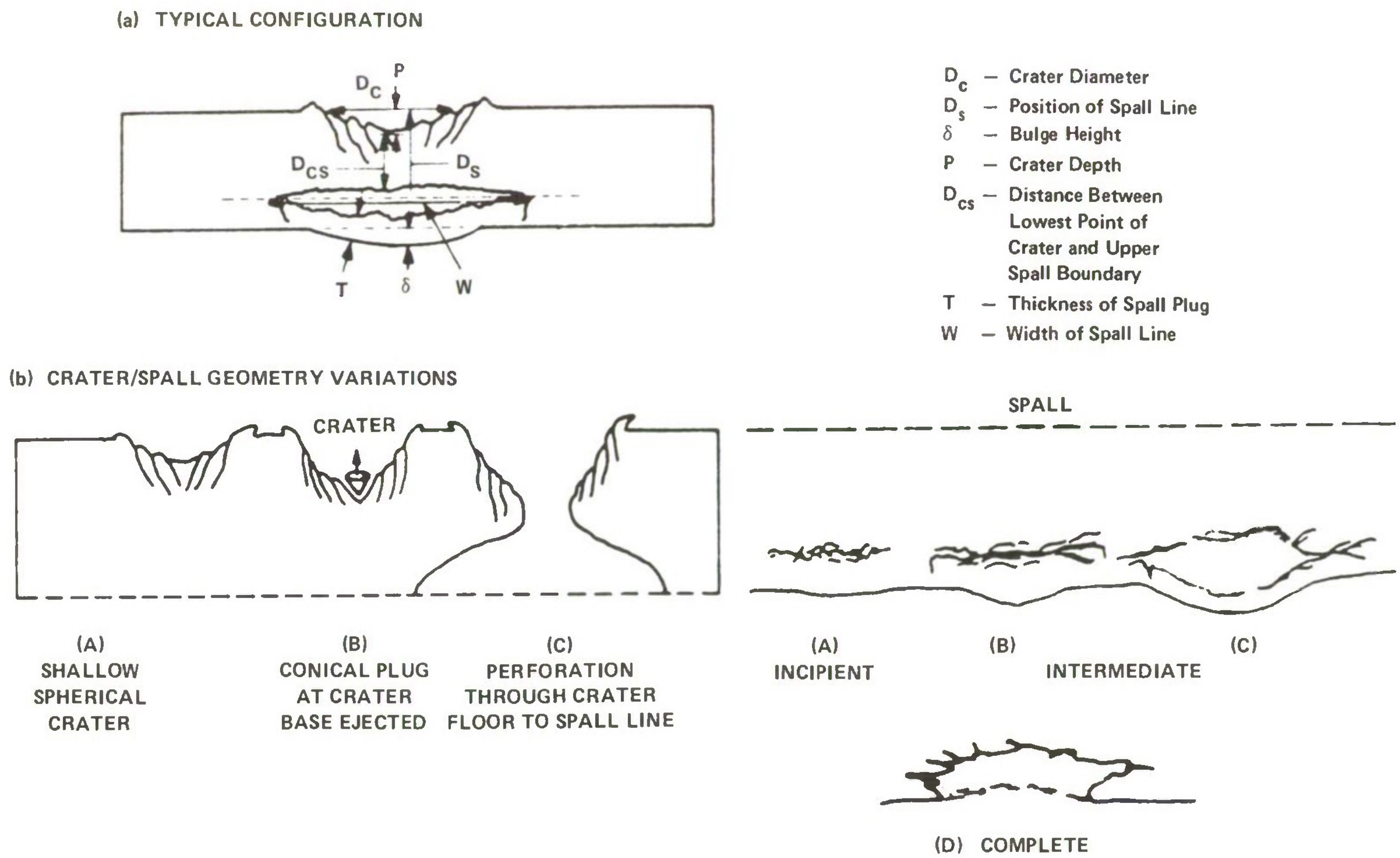

Figure 1. Impact damage geometries.

Below the center of the crater and about at the end of the macrocracks, there is an extensive network of fine microcracks. It has been hypothesized that these are adiabatic shear lines.[8] In the region of the microcracks, there are many relatively large voids. Most of these voids are intersected by one or more of the microcracks. The reason for the microcracks and voids is not known.

The spall layer is formed when the stress in the tensile wave reflected from the rear surface exceeds the spall threshold, measured at 38 kilobars for MS-12560 steel by Sandia Laboratories.[9] This is distinctly different from scabbing, which occurs when a penetrator or a shaped charge jet passes through the armor. In this latter case, some of the back surface surrounding the hole also may be ejected in the form of small fragments. This is often erroneously referred to as backface spallation. It has been suggested that armor can be hardened against scabbing by using homogeneous steel which has not been rolled parallel to the back surface.[10]

The backface bulge δ, which has the same thickness as the spall layer, increases exponentially with impact velocity, i.e.,

$$\delta = \delta_o \, e^{k(V - V_o)}. \qquad (1)$$

In this relation, δ_o is the thickness of the backface bulge at incipient spall, V_o is the corresponding velocity, and k is an empirical constant. This relation is plotted in Figure 2 for 0.953-centimeter nylon spheres impacting 1.25-centimeter-thick MS-12560 steel. It is seen that the experimental points fall remarkably well on the line. When the spall layer thickness becomes equal to the initial thickness of the spall plug (distance from the center of the spall layer to the backface), the backface is ejected in the form of a plug or as small fragments. Based on numerous experiments, the value for δ_o can be taken as 0.01 centimeter. As indicated above, the spall layer was generally parallel to the backface. Thus, a single spall measurement is sufficient to determine the velocity V_o required to cause backface spall.

In all cases where the projectiles were solid spheres and where backface spall resulted, the backface was ejected as a single plug. However, it was thought that a hollow sphere might cause backface spall at lower velocities than would solid spheres of the same weight (i.e., at equal impact kinetic energies); and it was thought that they might cause backface fragmentation. The reasoning behind these thoughts was that the impacting mass per unit area for the hollow sphere would be relatively small at the

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[8] D. A. Shockey, *et al., Physical Changes Occurring in Armor Steel Under Hypervelocity Impact,* Stanford Research Institute Final Report on USAMERDC Contract DAA D05-73-C-0025, March 1974.

[9] *Ibid.*

[10] M. Backman, Naval Weapons Center, Private Communication, April 1974.

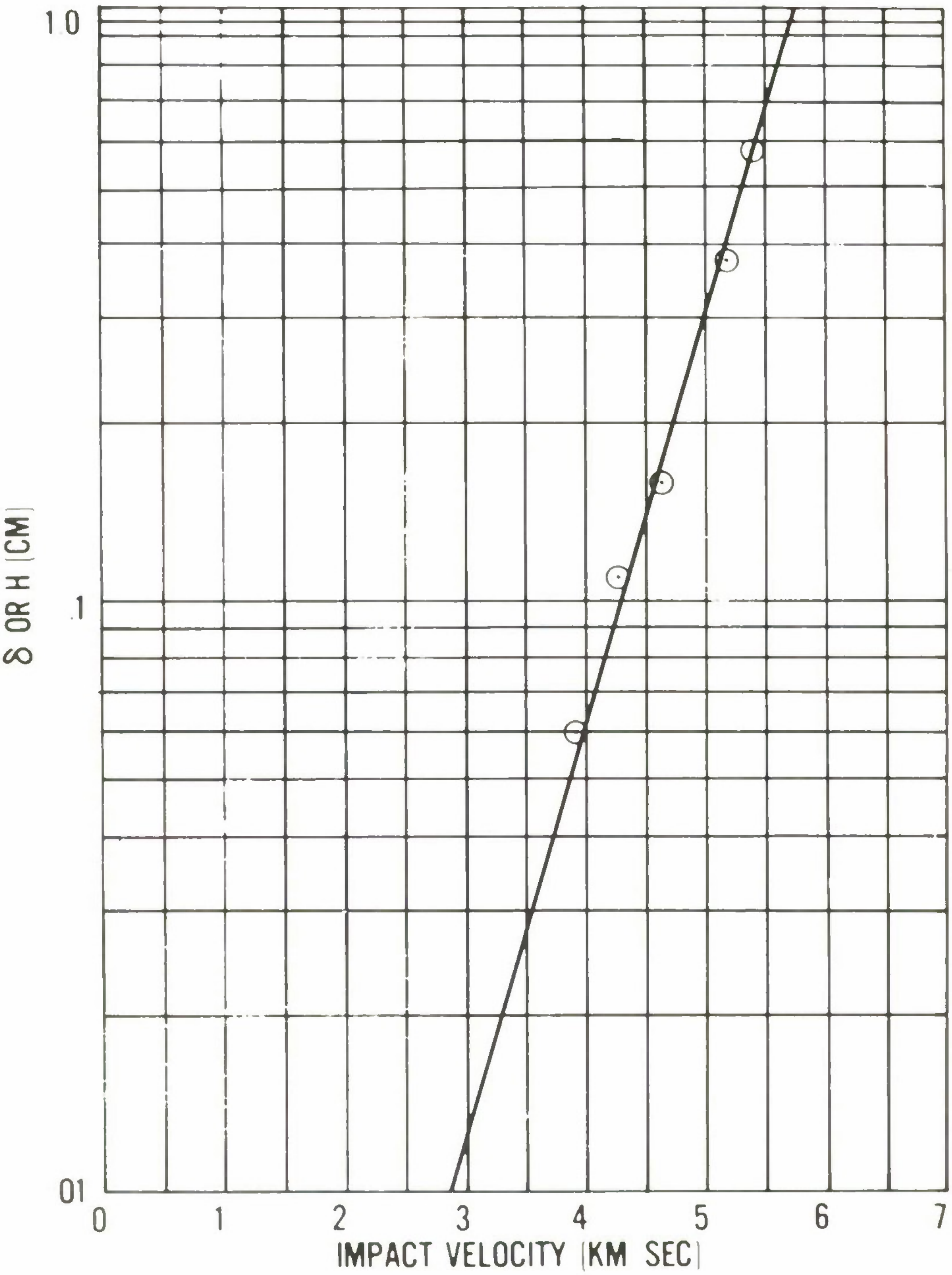

Figure 2. Backface bulge (or spall layer thickness) vs. impact velocity.

center, which would cause the spall layer to form nearer to the backface than it would for a solid sphere; the impacting mass per unit area would be large at the periphery, thus possibly resulting in an "irregular" compressive stress wave. The results of a few experiments seem to bear out these hypotheses, although more analysis is needed.

As a result of the hollow sphere experiments as well as other experiments, several computer-designed projectiles (spallators) were built for the purpose of optimizing backface fragmentation. These spallators were Lexan cylinders with impacting steel tips. They weighed 3.5 grams. On impacting 3-centimeter-thick wrought steel, the spallators caused 90 grams of the backface to fragment into more than a dozen pieces, which penetrated a 0.15-centimeter-thick aluminum witness plate. The spread in the eject angle was about 50°. Thus, these experiments clearly show that optimum spallators are feasible (a 200:1 mass eject ratio is the design goal).

III. RESULTS

4. **New Experiments.** When this research program first started in 1972, it was proposed that liquid projectiles be used. The liquid would, of course, be encased in some type of hollow shell, such as a hollow Lexan sphere, but most of the projectile mass would be in the form of a liquid. The reason for using liquids (mostly water) was because of their low sublimation energy. It was hypothesized that, at impact velocities of 5 to 10 km/s, a large amount of the impacting kinetic energy would go into vaporization of the projectile/target combination. Much of this energy would be lost; i.e., would not contribute to the process of shock formation in the target. Accordingly, it was felt desirable to have projectiles with a low sublimation (or vaporization) energy, such as water. Additional impact energy is lost because of penetration. Hence, low-density projectile materials were proposed.

One of the reasons for considering small projectiles was so that a large number of them could be loaded into a warhead and fired in a shotgun pattern, thus providing a large lethal radius. The primary target of concern was steel armor 2 to 3 centimeters thick. It was initially assumed that the projectile diameter should be approximately the same as the target thickness in order to alleviate loss of shock strength due to spherical divergence of the shock in the target. If the projectile mass is to be about 1 gram, this again suggests low-density material for the projectiles.

During the course of the early experimentation, it was found that the encased liquid projectiles often broke upon firing. This resulted in the loss of numerous test shots. In addition, the liquid would cause damage to the light gas-gun. Hence, solid plastics (mostly nylon), which have even lower sublimation energies (~ 200 cal/g), were used in place of the liquids. Experimental results for nylon and Lexan-encased water are about the same.

One of the experimental objectives was to determine the importance of sublimation energy as an impact parameter. An MgLi alloy (LA141A) with a density of 1.35 g/cm^3 has been used successfully for projectile materials. A spherical MgLi projectile (V = 5.2 km/s, D = 0.95 centimeter, and m = 0.65 gram) was fired against 1.25-centimeter-thick MS-12560 steel armor (Figure 3). In a qualitative way, it appeared to cause considerably more damage than comparable nylon spheres. The value of the sublimation energy is not presently available, but the melting point (~600° C) is considerably higher than for nylon; hence, the sublimation energy should be considerably higher. Thus, a tentative conclusion is that other parameters may be more important than sublimation energy. However, this is based on a single shot; and much more analysis is needed.

Two ceramics were tested, Al_2O_3 and WC. These have a high sublimation energy. The Al_2O_3 resulted in some spallation, but much less than for comparable nylon. The WC shot resulted in a very large and deep crater but no spallation. A tentative conclusion from these shots is that sublimation energy may be important.

A qualitative and partial explanation for some of these results can be obtained by comparing the impedances of the undamaged materials, although the geometry and impact conditions for the above shots are considerably different than those for which the following analysis holds.

An abrupt change in the physical properties of a material will result in the modification of a pressure pulse as it encounters this change. In general, a portion of the pulse will be transmitted, and a portion will be reflected. The relations which describe the modification of a pulse are based upon the boundary conditions of continuity of pressure and continuity of particle velocity across the interface between two materials. These relations depend upon the value of ρc, called the "characteristic impedance," of the two materials. If $\rho_o c_o$ is for the projectile and $\rho_1 c_1$ for the target, and if P_o is the effective pulse amplitude for the projectile, the amplitude of the component transmitted to the target is:

$$P_1 = \left[\frac{2\rho_1 c_1}{\rho_1 c_1 + \rho_o c_o}\right] P_o; \tag{2}$$

and the reflected component is:

$$P_r = \left[\frac{\rho_1 c_1 - \rho_o c_o}{\rho_1 c_1 + \rho_o c_o}\right] P_o. \tag{3}$$

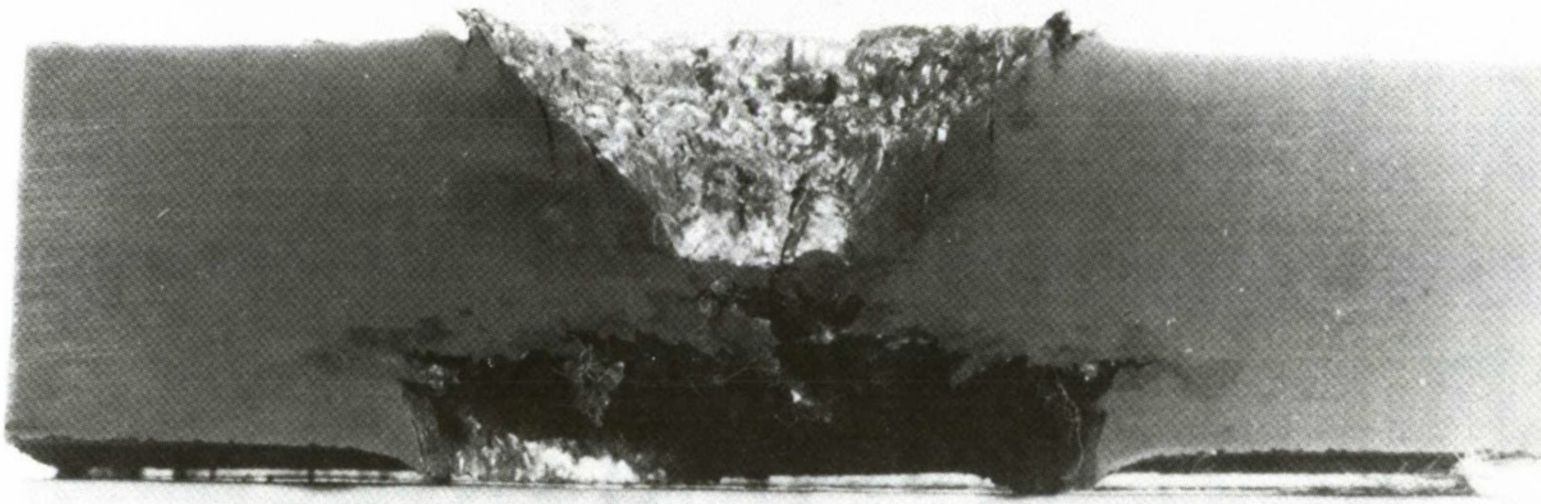

Figure 3. MgLi spherical projectile impact on 1.25-centimeter wrought steel. (V = 5.15 km/s, D = 0.953 centimeter, and m = 0.646 gram)

These relations are somewhat simplified by letting

$$K = \frac{\rho_t c_t}{\rho_o c_o} , \tag{4}$$

giving

$$\frac{P_t}{P_r} = \frac{2K}{K - 1} . \tag{5}$$

Values for this ratio are shown in the following table:

Impedance and Pressure Ratios for Various Projectile Materials

Material	Density (g/cm^3)	Sound Velocity (km/s)	ρc	K	P_t/P_r
WC	15.02	5.2	78	0.513	- 2.1
$Al_2 0_3$	3.95	9.9	39	1.03	6.8
Steel	7.9	5	40	1	0
Nylon	1.14	2.5	2.9	13.8	2.8
MgLi	1.35	4.25	5.9	6.8	2.34

Any conclusions drawn from these values must be considered tentative; however, there is reasonable qualitative agreement with experiment. For example, WC has a large impedance and a negative pressure ratio. This suggests that spallation should not be obtained as shown by experiment. On the other hand, impedanees for nylon and MgLi are low suggesting large spallation, also shown by experiment.

In attempting to develop damage eriteria, impact kinetic energy and impact momentum have been compared as parameters. According to Shockey et al.,[11] steel and nylon spherical projectiles cause about the same spallation damage at equal kinetic energies; but, on the basis of equal momenta, nylon is much more damaging than steel. Based on MERADCOM analysis, it is not elear that this is correct. Furthermore, the relevant damage parameters are not known; e.g., it is not known which is the more important parameter, energy or momentum.

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[11] D. A. Shockey, *et al., Physical Changes Occurring in Armor Steel Under Hypervelocity Impact,* Stanford Research Institute Final Report on USAMERDC Contract DAA D05-73-C-0025, March 1974.

ESR steel is made by a process of electroslag refining in which an ingot or rolled slab forms an electrode suspended in a water-cooled copper mold with its tip in a pool of specially formulated flux. The electrode is remelted by the flow of electric current from the tip through the flux and into the lower portion of the mold. The flux becomes superheated and melts the metal at the tip of the electrode, causing a continuous fall of droplets to form a new ingot below. In the process of melting and passage of droplets through the flux pool, the metal is refined. Accidental contaminates from refractories and oxidation during pouring are avoided. The undesirable elements, oxygen and sulfur, are reduced significantly, resulting in a steel that is extremely clean and virtually free from nonmetallic inclusions. What few inclusions remain are widely dispersed due to progressive solidification. MERADCOM tested a specimen of ESR steel 1.25 centimeters thick in the NRL light gas-gun facility. This specimen had a tensile strength of 21.6 kilobars, which is about twice that of the MS-12560 steel used in most of the previous tests. The Rockwell hardness was 55.3 at 30° C, about one-third greater than for the MS-12560 steel. The spherical nylon projectile weighed 0.52 gram and had a diameter of 0.95 centimeter. The impact velocity was 5.3 km/s. The resulting spallation is shown in Figure 4. The height of the backface bulge was 0.1 centimeter. From Figure 2, the corresponding height of the backface bulge for MS-12560 steel would have been 0.5 centimeter, although backface spall actually occurred at about 0.4 centimeter. Of particular interest is the shape of the spall layer. It is curved in a direction opposite to that of the bulge and has a much more pronounced curvature. In most of the previous tests, the spall layers of similar thickness were parallel to the backface bulge. Based on equation 1, the amount of ESR steel showing the same momentum damage as for MS-12560 steel would weigh 16 percent less; it would weigh 35 percent less if the parameter were impact kinetic energy.

It has been suggested that a piece of plastic on the backside of the armor would alleviate the backface spallation, or fragmentation, thus protecting soft interior components (of a military vehicle) from damage. This was tested on a 1.25-centimeter-thick MS-12560 steel target which had 0.9 centimeter of Plexiglas glued to the backface. The impacting spherical projectile was nylon at 0.5 gram and 0.95 centimeter diameter. The impact velocity was 5.3 km/s. The result is shown in Figure 5. The ejected Plexiglas was highly fragmented and would have done considerable damage to interior components. The ejected mass was about 40 times greater than the mass of the impacting nylon sphere. At the impact velocity of 5.3 km/s, the steel target would have exhibited backface spall. This type of damage was alleviated; however, it is seen from Figure 5 that a small backface bulge did occur. The impedance mismatch K between steel and Plexiglas is probably greater than an order of magnitude; hence, it is questionable that the ejected Plexiglas was due to spallation of the Plexiglas. Instead, it was probably due to simple displacement resulting from formation of the backface bulge in the steel, which occurred in about 0.1 second. An experiment to resolve this question will be performed in the near future.

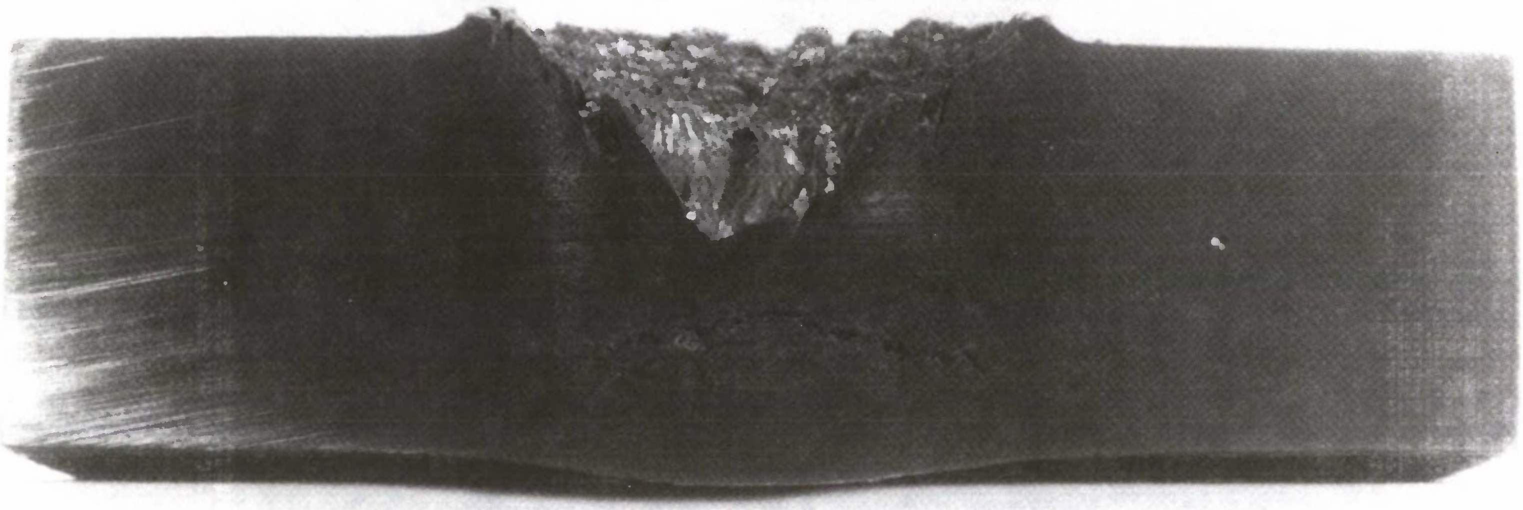

Figure 4. Nylon spherical projectile impact on 1.25-centimeter ESR steel.
(V = 5.31 km/s, D = 0.953 centimeter, and m = 0.52 gram)

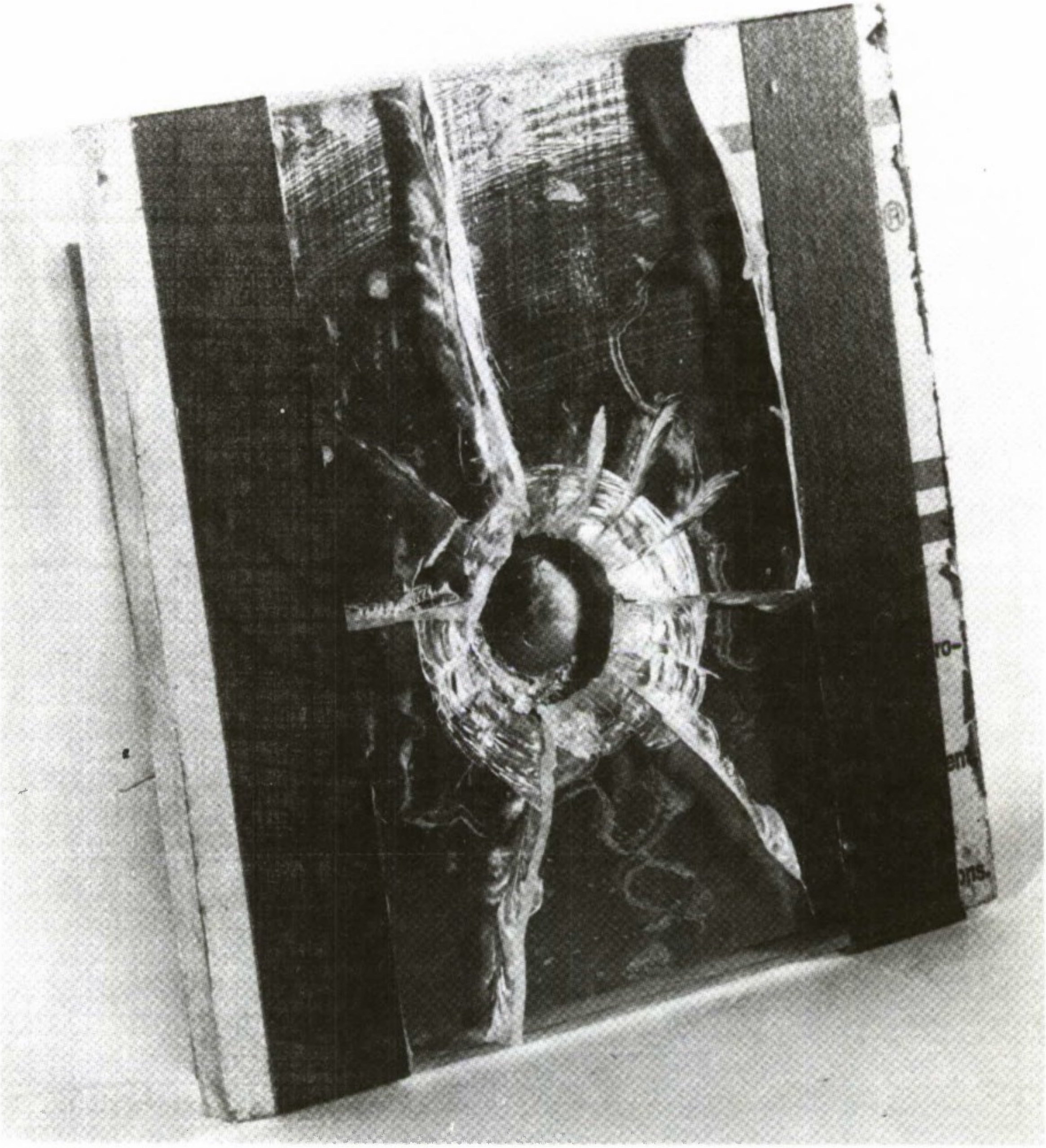

Figure 5. Nylon spherical projectile impact on wrought steel/Plexiglas target.
(V = 5.29 km/s, D = 0.953 centimeter, and m = 0.52 gram)

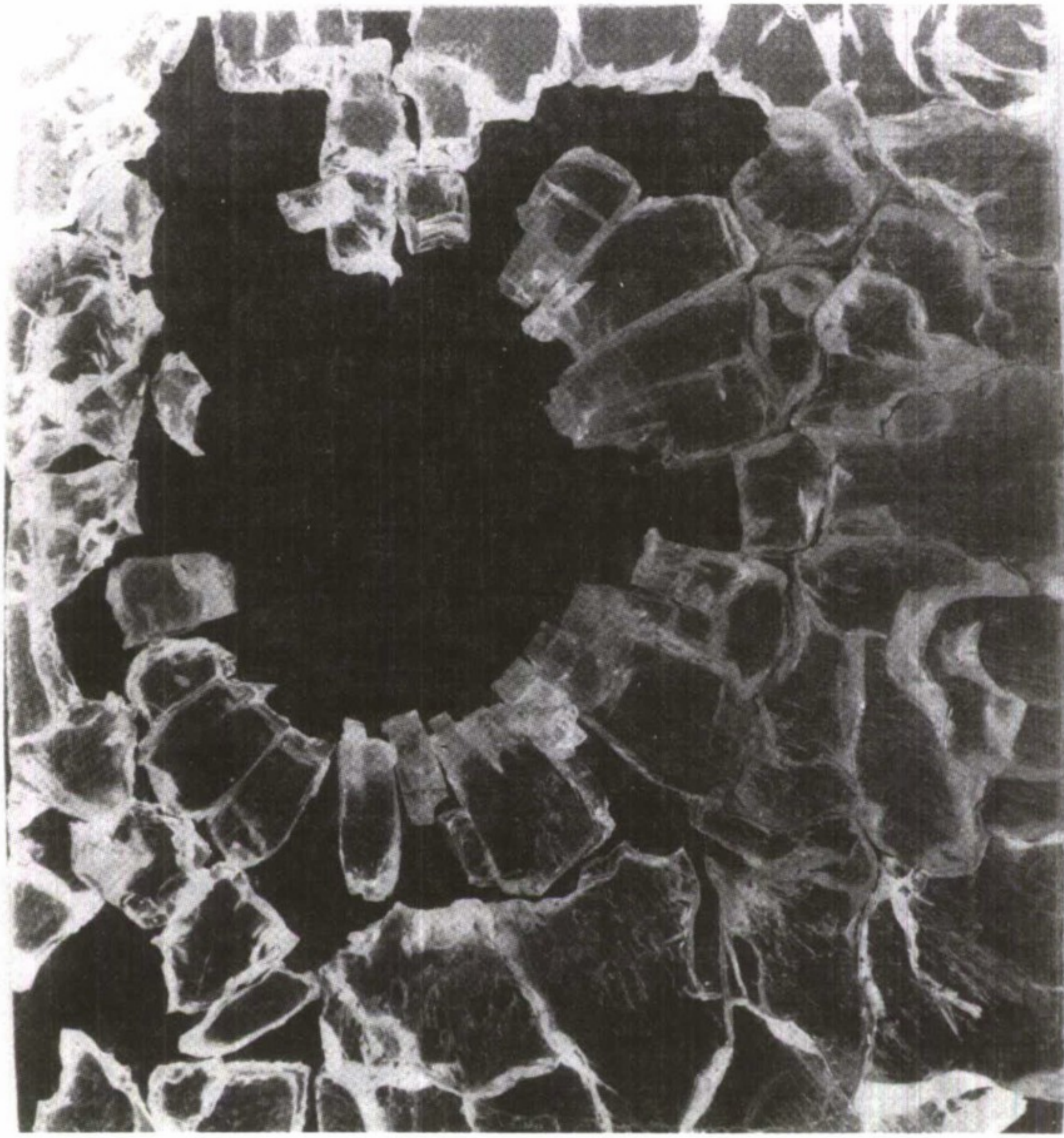

Figure 6. Nylon spherical projectile impact on wrought steel/Plexiglas target. (V = 5.22 km/s, D = 0.953 centimeter, and m = 0.52 gram)

Another interface experiment was made in which the Plexiglas was in front of the steel instead of behind. Everything else was the same as described in the preceding paragraph. In this case, the Plexiglas was shattered, as shown in Figure 6. There was virtually no damage to the steel armor. This seems to be an obvious result since most of the shock energy induced in the Plexiglas by the nylon projectile impact would reflect from the steel surface, as shown by the numbers in the table (page 9).

Finally, there are two other important and inexplicable results which have been reported previously.[12] The first is that smaller spheres cause relatively more damage than larger spheres. The second is somewhat more complicated. It is well known that martensitic steel exhibits the 130-kilobar phase change, as noted previously. It was further postulated that this phase change affected the stress pulse in such a way as to enhance spallation phenomena. Measurements show that austenitic steel does not exhibit the same phase change. However, an impact experiment on austenitic steel showed that the spallation was just as large and perhaps larger than for martensitic steel. It is apparent that there are many parameters involved and that their interdependency is largely unknown.

IV. SUMMARY AND CONCLUSIONS

5. **Summary and Conclusions.** New and important phenomena have been isolated. These include crater serrations, crater macrocracks, adiabatic shear lines and voids beneath the craters, and various aspects of the spall layer and backface spall. Some of the older phenomena have been delineated. These include the 130-kilobar phase change in martensitic steel and details of the spall layer. Further experiments have demonstrated that it is feasible to design a projectile for the specific purpose of optimizing backface spallation and fragmentation.

Perhaps the most important conclusion is that there are numerous parameters involved in hypervelocity impact-induced spall. These must be isolated and delineated in order to develop a heuristic spallation theory. The 2-d calculations are far too complicated and unreliable to use for predictive purposes.

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[12] D. A. Shockey, *et al., Physical Changes Occurring in Armor Steel Under Hypervelocity Impact,* Stanford Research Institute Final Report on USAMERDC Contract DAA D05-73-C-0025, March 1974.

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